Information Institute

Visiting Faculty Research Program

Summer Faculty Fellowship Program

Post-Doc Fellowship Program

2018 Research Topics

Rev-F

Visiting Faculty Research Program
Summer Faculty Fellowship Program
Post-Doc Fellowship Program

2018 Research Topics

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Advisor

Visiting Faculty Research Program
2018 Research Topics

Autonomy, C2, and Decision Support

Multi-Domain Mission Assurance

Jason Bryant
(315) 330-7670
Jason.Bryant.8@us.af.mil

In an effort to support the Air Force's mission to develop Adaptive Domain Control for increasingly integrated Mission Systems, we are interested in furthering the identification of problems, and development of solutions, in increasing Full-Spectrum Mission Assurance capabilities across joint air, space, and cyberspace operations. Modern multi-domain mission planning and execution integrates tightly with cyber and information infrastructure. To effectively direct and optimize complex operations, mission participants need timely and reliable decision support and an understanding of mission impacts that are represented and justified according to their own domain and mission context. We are interested in understanding, planning, and developing solutions for Mission Assurance that supports operations requiring Mission Context across multiple domains, and spans both Enterprise and constrained environments (processing, data, and bandwidth). The following topic areas are of interest as we seek to provide solutions that are domain adaptive, mission adaptive, and provide rich, critical situational awareness provisioning to Mission Commanders, Operators, and technologies that support autonomous Mission Assurance.

- Summary, Representation, and Translation of Multi-Domain Metrics of Mission Health - Expansive Mission Assurance requires adequate mechanisms to describe, characterize, and meaningfully translate mission success criteria, mission prioritization, information requirements, and operational dependencies from one domain to another in order to react to events, deliver them appropriately to mission participants, and thereby increase the agility, responsiveness, and resiliency of ongoing missions.
- Multi-Domain Command and Control information Optimization - Currently, information can be disseminated and retrieved by mission participants through various means. Increasingly, mission participants will face choices of what, how, and where information will reach them or be pushed back to the Enterprise. Deciding between C2 alternatives in critical situations requires increased autonomy, deconfliction, qualitative C2 mission requirements, and policy differentials. We are seeking representations, services, configuration management, and policy approaches towards solving multi-domain multi-C2 operations.

- Complex Event Processing for Multi-Domain Missions - The ability to better support future missions will require increased responsiveness to cyber, information, and multi-domain mission dynamics. We are seeking mission assurance solutions that process information event logs, kinetic operation event data, and cyber situational awareness in order to take data-driven approaches to validating threats across the full-spectrum of mission awareness, and justify decisions for posturing, resource and information management, and operational adjustments for mission assurance.
- Machine Learning for Mission Support - Decreasing the cost and time resource burdens for mission supporting technologies is critical to supporting transitioning to relevant domains and decreasing solution rigidity. To do this requires advanced approaches to zero shot learning in attempts to understand mission processes, algorithms to align active missions with disparate archival and streaming information resources, analysis of Mission SA to determine cross-domain applicability, and autonomous recognition of mission essential functions and mission relevant events. Additionally, ontologies and semantic algorithms that can provide mission context, critical mission analytics relationships, mission assurance provenance and response justifications, as well as mission authority de-confliction for intra-mission processes and role-based operational decisions, are topics that would support advanced capabilities for advanced mission monitoring, awareness, and assurance decisions.

Development of Physics-Based Space Operations Course of Action Tools

C Tyler Diggans
(315) 330-2102
Christopher.Diggans@us.af.mil

As more nations and corporate players enter the space domain, command and control in space becomes increasingly complex. Analytical tools are needed to enhance Space Situational Awareness, allowing for real time generation of suggested courses of action for avoiding or resolving common command issues. By leveraging mathematical tools and advances in machine learning, we can move toward a more agile and responsive management of space assets.

An in-house research effort is aimed at developing tools for incorporation into a C2 framework that is already established. Possible tools include automation of ground-based emitter Geo-location for interference signals, new launch detection and tracking capabilities, and applications of clustering in the space domain.

This work will include the following technical areas, which can serve as guidance for the desired background and/or interest in the project:

- Numerical analysis
- Orbital mechanics and reachability sets
- Statistics and machine learning
- Sensor and spectrum management
- Constrained non-linear optimization
- Complex systems and network dynamics

Optimized Machine Learning in Large-Scale and Complex Systems

Simon Khan
(315)-330-4554
Simon.khan@us.af.mil

The technological advances in communication, computing, and sensing have made it possible to practically realize large-scale networked systems engaged in data gathering and collaborative tasks. As a result, military operations are increasingly becoming complex due to availability of large amount of data, interconnectedness, and enhanced capabilities of data gathering platforms. These enhanced capabilities provide unprecedented opportunities for transforming battlespace operations. However, data processing and decision making tasks for these applications are extremely challenging from computational perspective due to large data sets, heterogeneity in data, large decision space, uncertainties, and dynamic and complex nature of interactions between units. Recent advances in machine learning techniques such as deep learning and Genetic-Fuzzy Trees have shown promise to address these challenges by providing approaches which are effective, reliably optimal, and computationally inexpensive. Such machine learning approaches aim to exploit data obtained from a large number of different scenarios executing in simulated or real-world environments. This topic seeks to develop optimal computational and machine learning paradigms that utilize large data sets to learn complex interdependencies in large data-sets and collaborative environments. Furthermore, evaluation of the approach in a dynamic and complex environment, and comparison of its performance with the traditional methods are required.

Digitizing the Air Force for Multi-Domain Command and Control (MDC2)

Ralph Kohler
(315) 330-2016
Ralph.Kohler@us.af.mil

This in-house research effort focuses on working on the Android Tactical Assault Kit (ATAK), which is an extensible, network-centric Moving Map display with an open Application Programming Interface (API) for Android devices developed by Air Force Research Laboratory (AFRL). ATAK provides a mobile application environment where warfighters can seamlessly exchange relevant Command and Control (C2), Intelligence Surveillance and Reconnaissance (ISR), and Situational Awareness (SA) information for domestic and international operations. This capability is key to the Department of Defense's (DoDs) goal of digitizing the Air Force for MDC2 efforts, because it serves as the backbone for connecting numerous platforms, people, and information sources.

Decentralized Planning for Command and Control

Kurt Lachevet
(315) 330-2896
Kurt.Lachevet@us.af.mil

In an effort to support the Air Force's mission to develop robust autonomous Command and Control (C2) systems in contested environments, we are interested in furthering the identification of problems, and development of solutions, in decentralized planning for C2. We are interested in planning solutions in resource-constrained environments (processing power, data, and communication restrictions) with time-sensitive goals. The following topic areas are of interest as we seek to provide a decentralized C2, collaborative planning capability to enable continued execution of plans in a contested environment.

- Mixed-Initiative Plan Adaptation – When communications with a centralized planning authority are compromised, the challenge becomes the continuity of operations at decentralized locations can become difficult. Capabilities of interest include effective methods of plan adaptation that don't require a complete re-planning phase in a centralized planning environment, and mixed-initiative plan adaptation solutions in a resource-constrained environment.
- Plan Deconfliction – As plans are successfully adapted to ensure mission continuity, how is re-synchronization effected when communications between distributed/decentralized C2 components are lost or compromised, and then restored – if at all. Local planning by distributed agents may be locally effective, but often leads to the need for later plan deconfliction and negotiation once communications resume and partial plans and plan fragments are aggregated. Finding effective ways to reduce the occurrence of initial plan conflicts as well as to minimize the amount of time required to de-conflict a set of partial plans is critical to time sensitive mission requirements. We are interested in plan de-confliction and synchronization solutions enabling inter-plan collaboration, efficient deconfliction, and plan (re)synchronization for autonomous/decentralized C2.

Mission Driven Enterprise to Tactical Information Sharing

James Milligan
(315) 330-4763
James.Milligan.2@us.af.mil

Forward deployed sensors, communication, and processing resources increase footprint, segregate data, decrease agility, slow the speed of command, and hamper synchronized operations. Required is the capability to dynamically discover information assets and utilize them to disseminate information across globally distributed federations of consumers spread across both forward-deployed tactical data links and backbone enterprise networks. The challenges of securely discovering, connecting to, and coordinating interactions between federation members and transient information assets resident on intermittent, low bandwidth networks need to be addressed. Mission prioritized information sharing over large-scale, distributed, heterogeneous

networks for shared situational awareness is non-trivial. The problem space requires investigation, potential solutions and technologies need to be identified, and technical approaches need to be articulated which will lead to capabilities that enable forward deployed personnel to reach back to enterprise information assets, and allow rear deployed operators the reciprocal opportunity to reach forward to tactical assets that can address their information needs.

- Anticipating versus Reacting - Conditions in real-world environments are dynamic - threats emerge and may be neutralized, opportunities appear without warning, etc. - and robust autonomous agents must be able to act appropriately despite these changing conditions. To this end, we are interested in identifying events which signal that a change must be made in one agent's behavior by mining past data from a variety of sources, such as its own history, messages from other autonomous agents, or other environmental sensors. This capability would allow agents to learn to anticipate and plan for scenario altering events rather than reacting to them after they have already occurred.

Reactive Service Migration

James Milligan
(315) 330-4763
James.Milligan.2@us.af.mil

Reactive service migration involves service fault detection and fail-over mechanisms, information service workload migration strategies to relieve overloaded network resources, and pre-positioning of information and services by recognizing the usage patterns of information consumers to anticipate their needs ahead of time. Reactive service migration fail-over mechanisms might make use of workflow compensation, service redundancy, or other exception handling techniques. Workload migration may involve the use of load balancing techniques to achieve optimal resource utilization, maximize throughput, minimize response time, and avoid overload. Pre-positioning of information and services might require the tracking and detection of events or changes in state which indicate an impending user need. In all cases, reactive service migration is concerned with optimizing the quality and availability of information management system services.

Context Sensitive Information Visualization to Enhance Situational Awareness

Jason Moore
(315) 330-4192
Jason.Moore.29@us.af.mil

Situational awareness is the "fabric" for collaboration and team synchronization in military operations. To be most enabling, its content and the presentation of that content must adapt to the information needs of individual team members, their tasks, and their current situation (context).

It must seamlessly bridge the strategic, operational and tactical levels of military operations supporting decisions and actions at all levels. We are looking for researchers to explore the science

of adaptive, context sensitive visualization of complex data rich environments, to support team self-synchronization/situation awareness and develop the underlying science needed to engineer future military systems.

Research areas of interest within this topic include:

- Visualization of complex information systems.
- Various techniques for de-cluttering data and the visualization of that de-cluttered data.
- Appropriate visualization abstractions that work over WebGL/Javascript or other browser enabled capabilities and languages
- Composable visualization system interfaces that reduce the amount of user end programming, but still offer rich expressivity
- Course of Action determination visualization system that presents the facets of information and the way the system derived the set and ranking of COAs

Connectivity and Dissemination

Blockchain-based Information Dissemination across Network Domains

Norman Ahmed
(315) 330-2283
Norman.Ahmed@us.af.mil

While crypto currency research has been around for decades, Bitcoin has gained a significant adaptation in recent years. Besides being an electronic payment mechanism, Bitcoin's underlying building blocks known as *blockchain*, has profound implications for many other computer security problems beyond cryptocurrencies such as a Domain Name System, Public Key Infrastructure, file storage and secure document time stamping.
The purpose of this topic is to investigate blockchain technologies, and develop decentralized highly efficient information dissemination methods and techniques for sharing and archiving information across network domains via untrusted/insecure networks (internet) and devices. Areas of consideration include but are not limited to: security design and analysis of the state of the art open source blockchain implementations (e.g., bitcoin), developing the theoretical foundation of blockchain-based techniques on different application domains, quantifying block mining efficiencies, block editing, and smart contracts in such domains.

Dynamic Resource Allocation in Airborne Networks

Elizabeth Bentley
(315) 330-2371
Elizabeth.Bentley.3@us.af.mil

From the Air Force perspective, a new research and development paradigm supporting dynamic airborne networking parameter selection is of paramount importance to the next-generation warfighter. Constraints related to platform velocity, rapidly-changing topologies, mission priorities, power, bandwidth, latency, security, and covertness must be considered. By developing a dynamically reconfigurable network communications fabric that allocates and manages communications system resources, airborne networks can better satisfy and assure multiple, often conflicting, mission-dependent design constraints. Special consideration will be given to topics that address cross-layer optimization methods that focus on improving the performance at the application layer (i.e. video or audio), spectral-aware and/or priority-aware routing and scheduling, and spectral utilization problems in cognitive networks.

Cognitive RF Spectrum Mutability

Michael Gudaitis
(315) 330-4478
Michael.Gudaitis@us.af.mil

John Matyjas
(315) 330-4255
John.Matyjas@us.af.mil

When considering operations across terrestrial, aerial, and space domains, effective use of the limited Electromagnetic Spectrum (EMS) for a multitude of purposes is critical. The combined pressures of increasing demand for services and less available bandwidth for all make it imperative to develop capabilities for more integrated, flexible and efficient use of available spectrum for all functions (communications, radar, sensors, electronic warfare, etc.) across all domains (terrestrial, aerial, and space). In recognition of the need for affordable, multi-functional software-defined radios with spectrum agility and survivability in contested environments, this research effort seeks lightweight Next-Generation Software Defined Radio (SDR++) architectures and advanced waveform components for affordable solutions based on COTS and non-development items (NDI), relevant operational security, and appropriate trades in levels of software & hardware roots-of-trust. This will create an innovative high-performance flexible radio platform developed to explore the use of next-gen cognitive, smart-radio concepts for advanced connectivity needs across heterogeneous waveform standards and multiple EMS use-cases; while meeting tighter cost budgets and shorter time-to-fielding. The technology developments will support global connectivity and interoperability via multi-frequency/band/waveform reprogrammable radios for networked, multi-node aerial layer connectivity & spectrum mutability, providing system composability and engineered resilience.

Wireless Optical Communications

David Hughes
(315) 330-4122
David.Hughes.16@us.af.mil

John Malowicki
(315) 330-3634
John.Malowicki@us.af.mil

Quantum communications research involves theoretical and experimental work from diverse fields such as physics, electrical engineering and computer science, and from pure and applied mathematics. Objectives include investigations into integrating quantum data encryption with a QKD protocol, such as BB84, and characterizing its performance over a free space stationary link. The analysis of the secrecy of the data is extremely important. Quantum-based encryption systems that use the phase of the signal as the information carrier impose aggressive requirements on the accuracy of the measurements when an unauthorized party attempts intercepting the data stream.

Free Space Optical Communication Links: Laser beams propagating through the atmosphere are affected by turbulence. The resulting wave front distortions lead to performance degradation in the form of reduced signal power and increased bit-error-rates (BER), even in short links. Objectives include the development of the relationship between expected system performance and specific factors responsible for wave front distortions, which are typically linked to some weather variables, such as the air temperature, pressure, wind speed, etc. Additional goals are an assessment of potential vulnerability of the quantum data encryption.

Associated with the foregoing interests are the design and analysis of simple to complex quantum optical circuitry for quantum operations. Characterization of entanglement in states propagating through such circuits in terms of measures such as PPT, CSHS inequalities, and entropic techniques are of interest.

Wireless Sensor Networks in Contested Environments

Lauren Huie
(315) 330-3187
Lauren.Huie-Seversky@us.af.mil

Nishant Zachariah
Nishant.Zachariah@us.af.mil

Sensor networks are particularly versatile for a wide variety of detection and estimation tasks. Due to the nature of communication in a shared wireless medium, these sensors must operate in the presence of other co-located networks which may have competing, conflicting, and even adversarial objectives. This effort focuses on the development of the fundamental mathematics necessary to analyze the behavior of networks in contested environments. Security, fault tolerance, and methods for handling corrupted data in dynamically changing networks are of interest.

Research areas include but are not limited to optimization theory, information theory, detection/estimation theory, quickest detection, and game theory.

Development of new cryptographic techniques is not of interest under this research opportunity.

Airborne Networking and Communications Links

Michael Medley
(315) 330-4830
Michael.Medley@us.af.mil

John Matyjas
(315) 330-4255
John.Matyjas@us.af.mil

This research effort focuses on the examination of enabling techniques supporting potential and future highly mobile Airborne Networking and Communications Link capabilities and high-data-rate requirements as well as the exploration of research challenges therein. Special consideration will be given to topics that address the potential impact of cross-layer design and optimization among the physical, data link, and networking layers, to support heterogeneous information flows and differentiated quality of service over wireless networks including, but not limited to:

- Physical and MAC layer design considerations for efficient networking of airborne, terrestrial, and space platforms;
- Methods by which nodes will communicate across dynamic heterogeneous sub-networks with rapidly changing topologies and signaling environments, e.g., friendly/hostile links/nodes entering/leaving the grid;
- Techniques to optimize the use of limited physical resources under rigorous Quality of Service
- (QoS) and data prioritization constraints;
- Mechanisms to handle the security and information assurance problems associated with using new high-bandwidth, high-quality, communications links; and
- Antenna designs and advanced coding for improved performance on airborne platforms.

THz Communication – Materials and Mechanisms

Michael Medley
(315) 330-4830
Michael.Medley@us.af.mil

Rebecca Cortez
(315) 330-3150
Rebecca.Cortez@us.af.mil

THz communication holds promise to increase wireless data rates over short distances. This may be achieved using emerging technologies based on nanostructured materials. Potential material candidates may include carbon based nanomaterials or other plasmonic materials. This research effort focuses on understanding the materials and mechanisms which allow for the transmission of THz frequency signals. Topics of interest include theoretical examination of the physical

mechanisms responsible for propagating the THz signals from source to receiver; design and fabrication strategies for component development (transmitters or receivers) capable of supporting THz frequencies; and analytical exploration of component efficiencies to minimize free space loss.

Computational Trust in Cross Domain Information Sharing

Colin Morrisseau
(315) 330-4256
Colin.Morrisseau@us.af.mil

Yat Fu
(315) 330-4950
Yat.Fu@us.af.mil

In order to transfer information between disjointed networks, various domains, or disseminate to coalition partners, Cross Domain Solutions (CDS) exist to examine and filter information that ensures only appropriate data is released or transferred. Due to the ever increasing amount of data needing to be transferred and newer, more complex data format or protocols created by different applications, the current CDSs are not keeping up with the current cross domain transfer demands. As a result, critical information is not being delivered to the decision makers in a timely manner, or sometimes, even at all. In order to meet today's cross domain transfer needs, CDSs are looking to employ newly emerging technologies to better understand the information that they use to process and adapt to large workloads. These emerging technologies include, but are not limited to, machine learning based content analysis, information sharing across mobile and Internet of Things (IoT) based devices, cloud based cross domain filtering systems, passing information across nonhierarchical classifications and processing of complex data such as voice and video. While adding these new technologies enhance CDSs' capabilities, they also add a substantial complexity and vulnerabilities to the systems. Some common attacks may come from a less critical network trying to gain critical network access, or malware on the critical-side trying to send data to the less critical side. Research should investigate and examine methods to efficiently secure emerging technologies beneficial to CDSs. Researchers will collaborate heavily with the AFRL's cross domain research group for better understanding of cross domain systems as they apply their specific areas of emerging technology expertise to these problems. The expected outcome may include a design and/or a proof of concept prototype to incorporate emerging technologies into CDSs. It may also include vulnerability analysis and risk mitigation for those emerging technologies operated in a critical environment.

Next-generation Aerial Directional Data Link & Networking (NADDLN)

Nathaniel Rowe
(315) 330-7047
Nathaniel.Rowe.1@us.af.mil

John Matyjas
(315) 330-4255
John.Matyjas@us.af.mil

Given the scarcity of spectrum, there is a desire to develop self-forming, self-managing directional tactical data links operating at higher frequencies. Directional networking provides an opportunity to increase spectral efficiency, support ad-hoc aerial connectivity, improve resistance to intended/unintended interference, and increase the potential capacity of the link. However, complexity is added to the pointing, acquisition and tracking (PAT) required to establish and maintain a network of directional links over omnidirectional systems. Research interests reside in (1) the ability to make real-time content/context-aware trades involving capacity, latency, and interference tolerance; (2) mission-aware link and network topology control; and (3) affordable apertures and PAT systems; ultimately, to deliver new capabilities for next-generation aerial directional data link & networking (NADDLN).

Advanced High Speed Data Links

Yassir Salama
(315) 330-4977
Yassir.Salama.1@us.af.mil

This in-house research effort focuses on very high speed data links (multi-gigabits) built on commercial standards such as IEEE std. 802.16 We are exploring the advantages of using orthogonal frequency division multiplexing and multi-access (OFDM, and OFDMA). In order to achieve multi-gigabit performance, we are investigating the use of an ultra wide band communication scheme with high order modulation techniques. Several challenge topics need to be investigated in this project. These topics include, but are not limited to:

- Doppler Frequency spread for ultra wide band communication systems using OFDM/OFDMA in high mobility airborne environment
- Peak-to-Average Power Ratio (PAPR) mitigation in OFDM communication system
- Clock and Carrier recovery techniques in very high speed communication systems
- Time and Frequency synchronization in OFDM/OFDMA communication systems
- Real-time high efficiency Forward Error Correction (FEC) techniques using state-of-the-art FPGA design

Complex Network and Information Modeling & Inference

Lee Seversky
(315) 330-2846
Lee.Seversky@us.af.mil

Lauren Huie
(315) 330-3187
Lauren.Huie-Seversky@us.af.mil

Eric Heim
(315)-330-7084
Eric.Heim.1@us.af.mil

Recent advances in sensing technology have enabled the capture of dynamic heterogeneous network and information system data. However, due to limited resources it is not practical to measure a complete snapshot of the network or system at any given time. This topic is focused on inferring the full system or a close approximation from a minimal set of measurements. Relevant areas of interest include matrix completion, low-rank modeling, online subspace tracking, classification, clustering, and ranking of single and multi-modal data, all in the context of active learning and sampling of very large and dynamic systems. Applications areas of interest include, but are not limited to communication, social, and computational network analysis, system monitoring, anomaly detection, video processing. Also of interest are topological methods such as robust geometric inference, statistical topological data analysis, and computational homology and persistence. The exploration of new techniques and efficient algorithms for topological data analysis of time-varying and dynamic systems is of particular interest. Candidates should have a strong research record in these areas.

Quantum Networking with Atom-based Quantum Repeaters

Kathy-Anne Soderberg
(315) 330-3687
Kathy-Anne.Soderberg@us.af.mil

A key step towards realizing a quantum network is the demonstration of long distance quantum communication. Thus far, using photons for long distance communication has proven challenging due to the absorption and other losses encountered when transmitting photons through optical fibers over long distances. An alternative, promising approach is to use atom-based quantum repeaters combined with purification/distillation techniques to transmit information over longer distances. This in-house research program will focus on trapped-ion based quantum repeaters featuring small arrays of trapped-ion qubits connected through photonic qubits. These techniques can be used to either transmit information between a single beginning and end point, or extended to create small networks with many users.

Agile Networking for the Aerial Layer

Amjad Soomro
(315) 330-4694
Amjad.Soomro@us.af.mil

John Matyjas
(315) 330-4255
John.Matyjas@us.af.mil

The characteristics of today's aerial layer networks are limiting effective information sharing and distributed command & control (C2), especially in contested, degraded, operationally limited environments, where the lack of interoperability and pre-planned/static link configurations pose the greatest challenges. Advanced research in wireless networking is sought to support aerial information exchange capabilities in highly dynamic environments. This includes but is not limited to: disruption/delay tolerant networking; radio-to-router interface protocols; opportunistic transport protocols; resilient data/message protocols and on-demand prioritization; spectrum use; infrastructure sharing and mesh networking.

Software Defined Networking

Amjad Soomro
(315) 330-4694
Amjad.Soomro@us.af.mil

John Matyjas
(315) 330-4255
John.Matyjas@us.af.mil

Software Defined Networking (SDN) is a recent trend in computer networking with strong vendor support that allows a software program to control the behavior of an entire network. SDN separates a network's control logic from the underlying data forwarding plane, which allows network operators to write high-level multi-mission policies and define complex tasks to dynamically control network and its resources to meet on-demand in-theater mission requirements while mitigating vulnerabilities and threats in cyber and Electro Magnetic (EM) domains.

The topic seeks highly motivated research on how SDN can support dynamic, resilient local and global command & control (C2) for joint tactical edge network (JTEN) operations. For example, high level network control makes it possible for operators to specify more complex tasks that involve integrating many disjoint network functions (e.g., security, resource management, and prioritization, etc.) into a single control framework, which enables (1) mapping mission/application level requirements to a set of tangible network configurations, (2) robust and agile network reconfiguration and recovery, (3) flexible network management and planning, and, in turn, (4) improvements in network efficiency, controllability, and survivability.

Ultra-broadband Networking: mm-Waves, THz Band and Beyond

Ngwe Thawdar
(315) 330-2951
Ngwe.Thawdar@us.af.mil

Scott Pudlewski
(315) 330-4405
Scott.Pudlewski.1@us.af.mil

Today's increasing demand for higher data rates and congestion in conventional RF spectrum have motivated research and development in higher frequency bands such as millimeter-wave, terahertz band and beyond. New developments in device and physical layer technologies promise to relieve the overcrowded spectrum at lower frequencies as well as enable new high-bandwidth applications that are not feasible with current wireless technologies. The focus of this research is to develop novel networking solutions that will exploit the full potential of unprecedentedly large bandwidth offered by the recent developments in high-frequency bands.

Traditionally, wireless networks have been designed with the major constraint being available bandwidth. We are interested in new and novel protocols at higher layers that do not hold the same assumption but address the challenges stemming from the peculiarities of channel physics at high frequencies. For example, very high path loss caused by atmospheric and molecular absorption at these frequencies have effectively shorten the transmission range. This, in turn, calls for deployment of highly directional antennas and massive-MIMO arrays as well as relaying and multi-hop communication schemes. In this new paradigm, our research areas of interest includes but are not limited to:

- Link layer protocols where nodes do not need to aggressively contend for the channel but have to consider challenges stemming from channel characteristics and use of directional antennas.
- Transport and network layer protocols that can support very high data arrival rates without data loss or queueing issues.
- Topology control of ultra-dense networks consisting of active and passive relay nodes and nodes using directional and massive-MIMO antenna arrays.
- Synchronization and medium access strategies that consider the effect of very high-speed data rates (Tbps or at least multi-Gbps) in high-speed airborne networks.
- Compatibility with legacy frequency band access to provide spectrum diversity to the system.

Cross-layer protocols that take into account of challenges and opportunities at higher frequency bands.

Cyber Science and Technology

Cyber Agility Research and Applications

Norman Ahmed
(315) 330-2283
Norman.Ahmed@us.af.mil

Traditional defensive security solutions employ techniques such as parameter-based defenses, data encryption, attribute-based access control, redundancy and replications, to safeguard systems. With the rise of sophisticated cyber-attacks from intelligent adversaries in recent years, given sufficient time and resources, all of these methods can be defeated. Moving Target Defense (MTD) is a promising new defensive security solution that aims to change the adversary's gain-loss balance by continuously shifting a system's attack surface.

The purpose of this topic will be to develop novel methods of dynamic MTD solution approaches for high and low bandwidth networks and platforms/devices. The fundamental research areas of interest within this topic include, but are not limited to:

- Methods for application/library segregation, diversification, randomization and data fragmentations for dynamically computing and migrating applications across platforms/devices (Mobile/servers).
- An end-to-end MTD solution approaches that span from application layer to the firmware.

Network Defense through Dynamic Attack Surfaces

Norman Ahmed
(315) 330-2283
Norman.Ahmed@us.af.mil

David Myers
(315) 330-2988
David.Myers.35@us.af.mil

Today, information system defenders face an asymmetric disadvantage against attackers. Current information system defenses (at the network, host machine, and lower levels) are static, keeping the same configuration over time with little or no change. Consequently, attackers may perform reconnaissance at their own leisure and launch attacks when they are ready. In response to this situation, a new class of defenses has been developed, called Moving Target Defenses (MTDs; also called cyber agility techniques). MTDs dynamically change the configuration of defenses and/or target machines over time, thus shortening the reconnaissance/plan/attack cycle available to the adversary. MTDs come in many forms, such as at the network level (e.g. IP-hopping, port-hopping), host machine level (e.g. OS hopping using multiple VMs to host a web service), and lower levels (e.g. Address Space Randomization, Instruction Set Randomization).

Although a fair amount of work has been done to develop MTDs, little work has been done to study the effects or optimal deployment of MTDs. This research seeks to develop the science of MTD effect analysis for the optimal deployment of MTDs in relation to the resource and security requirements of the set of missions currently operating on the information system. Possible areas of research include MTD characterization (to quantify the security provided and resources consumed by a given MTD), mission mapping (to determine the resource and security requirements of an active cyber mission), or optimal MTD deployment with a focus on preventing cyber friendly fire (MTDs interfering with each other or any of the active cyber missions).

Foundations of Resilient and Trusted Systems

Steven Drager
(315) 330-2735
Steven.Drager@us.af.mil

Research opportunities are available for T model-based design, development and demonstration of foundations of resilient and trustworthy computing, including technology, components and methods supporting a wide range of requirements for improving the resiliency and trustworthiness of computing systems via multiple resilience and trust anchors throughout the system life cycle including design, specification and verification of cyber-physical systems.. Research supports security, resiliency, reliability, privacy and usability leading to high levels of availability, dependability, confidentiality and manageability. Thrusts include hardware, middleware and software theories, methodologies, techniques and tools for resilient and trusted, correct-by-construction, composable software and system development. Specific areas of interest include: Automated discovery of relationships between computations and the resources they utilize along with techniques to safely and dynamically incorporate optimized, tailored algorithms and implementations constructed in response to ecosystem changes; Theories and application of scalable formal models, automated abstraction, reachability analysis, and synthesis; Perpetual model validation (both of the system interacting with the environment and the model itself); Trusted resiliency and evolvability; Compositional verification techniques for resilience and adaptation to evolving ecosystem conditions; Reduced complexity of autonomous systems; Effective resilient and trusted real-time multi-core exploitation; Architectural security, resiliency and trust; Provably correct complex software and systems; Composability and predictability of complex real-time systems; Resiliency and trustworthiness of open source software; Scalable formal methods for verification and validation to prove trust in complex systems; Novel methodologies and techniques which overcome the expense of current evidence generation/collection techniques for certification and accreditation; and A calculus of resilience and trust allowing resilient and trusted systems to be composed from untrusted components.

Polymorphic Code for Resilient Cyber-Physical Systems

Eric Lam
(315) 330-3298
Eric.Lam.3@us.af.mil

Cyber-physical systems interact with the physical world. Just like living organisms, cyber-physical systems will need to adapt to the changing environment to optimize their missions or reduce cyber-vulnerability. Concepts and code is required in Cyber-physical systems that can interpret physical events and 'evolve' base code to create a response. This will have applications in IoT and ICS defense. The initial phase will to develop base code that will interact with the CPS system and physical stimuli in a control way. This will lead future development in artificial intelligence and machine-learning to add resilient code.

Research areas of interest within this topic include:

- Cyber-physical systems
- Polymorphic software
- Machine-Learning
- Bio-inspired software

Trusted Software-Intensive Systems Engineering

William McKeever
(315) 330-2987
William.McKeever.1@us.af.mil

Software is a prime enabler of complex weapons systems and its fungible nature is key to the development of next generation adaptive systems.

Yet, software is the most problematic element of large scale systems, dominated by unmet requirements and leading to cost and schedule overruns. As the complexity of today's system lies in greater than 10^5 requirements, 10^7 lines of code, thousands of component interactions, 30 year product life cycles and stringent certification standards. The tools used to design, develop and test these complex systems do little to instill trust that the software is free from vulnerabilities, malicious code or that it will function correctly. Furthermore there is virtually no tool capable of detecting design flaws. The objective of the trusted software-intensive systems engineering topic is to develop techniques and tools to enable trust (with a focus on security and correctness) throughout the software lifecycle.

Areas of interest include: evidence-based software assurance; static analysis tools with a preference to analysis at the binary level; algorithm or design-level analysis; secure software development; model-based software engineering; correct-by-construction software generation.

Active Sampling Approaches Applied to Complex Cyber Experimentation

David Myers
(315).330.2988
David.Myers.35@us.af.mil

Standard design of experiments work well for experiments with a small number of controllable input parameters. As the number of input parameters grows, static experimental designs begin to fail. In the cyber domain, online control of experimentation is required in order to produce valuable experimental data. This research seeks to explore the application of active sampling techniques/algorithms to complex cyber experimentation data. These algorithms have typically been explored only in a theoretical setting and we look to apply them to real world data sets. This research is looking to explore a wide range of these algorithms, to potentially include bandit problems and other machine learning approaches for real-time experimental design.

Application of Game Theory and Mechanism Design to Cyber Security

Laurent Njilla
(315) 330-4939
Laurent.Njilla@us.af.mil

Cyber attacks pose a significant danger to our economic prosperity and national security whereas cyber security seeks to solidify a scientific basis. Cyber security is a challenging problem because of the interconnection of heterogeneous systems and the scale and complexity of cyberspace. This research opportunity is interested in theoretical models that can broaden the scientific foundations of cyber security and develop automated algorithms for making optimum decisions relevant to cyber security. Current approaches to cyber security that overly rely on heuristics have been demonstrated to have only limited success. Theoretical constructs or mathematical abstractions provide a rigorous scientific basis for cyber security because they allow for reasoning quantitatively about cyber attacks.

Cyber security can mathematically be modeled as a conflict between two types of agents: the attackers and the defenders. An attacker attempts to breach the system's security while the defenders protect the system. In this strategic interaction, each agent's action affects the goals and behaviors of others. Game theory provides a rich mathematical tool to analyze conflict in strategic interaction and thereby gain a deep understanding of cyber security issues. The Nash equilibrium analysis of the security games allows the defender to allocate cyber security resources, understand how to prioritize cyber defense activities, evaluate the potential security risks, and reliably predict the attacker's behavior.

Securing cyberspace needs innovative game theoretic models that consider practical scenarios such as: incomplete information, imperfect information, repeated interaction and imperfect monitoring. Moreover, additional challenges such as node mobility, situation awareness, and computational complexity are critical to the success of wireless network security. Furthermore, for making decisions on security investments, special attention should be given to the accurate value-added

quantification of network security. New computing paradigms, such as cloud computing, should also be investigated for security investments.

We also explore novel security protocols that are developed using a mechanism design principle. Mechanism design can be applied to cyber security by designing strategy-proof security protocols or developing systems that are resilient to cyber attacks. A network defender can use mechanism design to implement security policies or rules that channel the attackers toward behaviors that are defensible (*i.e.*, the desired equilibrium for the defender).

Cyber Security Research and Applications for Cyber Defense

Laurent Njilla
(315) 330-4939
Laurent.Njilla@us.af.mil

Cyberspace remains beneficial and a technological advantage with vulnerabilities under control. Cyber Defense is concerned with the protection and preservation of critical information infrastructures available in cyberspace. The Air Force's mission to fly and fight in Air, Space, and Cyberspace involve the technologies to provide information to the warfighters anywhere, anytime, and for any mission. This far-reaching endeavor will necessarily span multiple networks and computing domains not exclusive to military.

Economics also known as the study of resource allocation problems, has always been a factor in engineering. Economics is sought to provide the answer to managing large-scale information systems. The introduction of mobile agents, autonomy, computational economy, pricing mechanisms, and game theory mechanisms will strive to unveil the same phenomena as a real one; it will admit arbitrary scale, heterogeneity of resources, decentralized operation, and tolerance in presence of vulnerability.

This technology area seeks to: 1) protect our own information space through assurance; 2) enable our system to automatically interface with multi-domain systems through information sharing with ability to deal with unanticipated states and environments; 3) provide the means to circumvent by learning new configurations and understand vulnerabilities before their exploitation, and 4) reconstitute systems, data, and information from different domains rapidly to avoid disruptions.

Fundamental research areas of interest within this topic include (cryptographic techniques is not of interest under this research opportunity):

- Design of systems composed of both trusted and untrusted hardware and software; study of virtualization of hardware components and platforms with configurability on-the-fly.
- Mathematical concepts and distinctive mechanisms that enable systems to automatically continue correct operation in the presence of unanticipated input or an undetected bug or vulnerability.
- Examination of assumptions, mechanisms, and implementations of security modules with capability to rewrite itself without human interactions in the presence of unwanted/unanticipated configurations.

- Information theory and Category theory describing interactions of systems of systems that lead to better consideration of their emergent behaviors during attack and reconstitution; models used to predict system responses to malwares and coordinated attacks as well as analyses of self-healing systems.

Cyber Threat Avoidance and Mining Process

Laurent Njilla
(315) 330-4939
Laurent.Njilla@us.af.mil

The security landscape is becoming more sophisticated, with the emergence of new communication technology platforms and information, such as mobile computing, cloud computing, online social networks, cyber physical system and the Internet of Things (IoT). An alleged unmotivated form of vandalism before on the Internet has become a diverse ecosystem of cyber-crime, where providers and consumers come together to achieve various end-goals and utilities. The persistence, complexity, and capabilities of today's adversaries are limitless, and their threat does not only affect individuals or organizations, but also nations.

Traditional firewalls are not sufficient to ensure the security of computer networks. Due to the interconnection of numerous networks, the cyberspace is becoming vulnerable to cyber attacks. There is a need to strike a balance between firewalls and other protective mechanisms. Amongst these mechanisms, intrusion detection and the profiling of attackers are mostly used despite their limitations. However, some data mining techniques such as 1) deep neural networks, 2) clustering and machine learning can be used. The use of Process mining techniques combined with game theoretic concepts can bridge the gap for discovering security breaches and learning the attackers' modus operandi.

Moreover, research work have proposed sharing cyber threat information as a mean to prevent future cyber attacks and revenue loss by finding and repairing the vulnerabilities proactively. Information sharing also minimize the cost of investment in developing countermeasure to cyber attacks. This research opportunity is interested in applying new techniques such as Category theory, channel theory, and information flow to tackle cyber threat information sharing and side channel attack.

Market-Based and Game Theoretic Methods for Resource Allocation in the Cloud

Laurent Njilla
(315) 330-4939
Laurent.Njilla@us.af.mil

Information systems are continually expanding as evidenced by the doubling of Internet connections every year. Similar growth is exhibited by information systems in defense. The Air Force's mission to fly and fight in Air, Space, and Cyberspace involve the technologies to provide information to the warrior anywhere, anytime, and for any mission. This far-reaching enterprise will necessarily span multiple networks and computing domains that include those that are commercial and exclusively military. As a result, many users with different goals and priorities vie for the communication and computing resources. Managing this vast system to ensure dependable operation that maintains users' quality of service levels has led researchers to propose computational markets as a means for controlling the allocation of system resources. Economics has always been a factor in engineering. Because it is also the study of resource allocation problems, economics is sought to provide the answer to managing large-scale information systems. By introducing software agents, pricing mechanisms, and game-theoretic mechanisms, the computational economy will strive to exhibit the same phenomena as a real one; it will admit arbitrary scale, heterogeneity of resources, decentralized asynchronous operation, and tolerance of localized failures. These derived benefits are compelling and recent advances in cloud computing have created opportunities for the serious contemplation of building computational markets.

Cyber Defense Research

E. Paul Ratazzi
(315) 330-3766
Edward.Ratazzi@us.af.mil

Cyber Defense is concerned with the protection and preservation of critical information infrastructures in order to ensure the United States' dependency on cyberspace remains beneficial and does not turn a technological advantage into a vulnerability.

This technology area seeks to: 1) protect our own information space through assurance, agility, denial, deception, and deterrence; 2) enable our system to automatically survive attacks through an innate ability to deal with unanticipated states and environments; 3) provide the means to identify, understand, attribute and localize vulnerabilities before they are exploited, and attacks as they occur; and 4) recover and reconstitute systems, data, and information states rapidly to ensure continuity of operations.

Fundamental research areas of interest within this topic include:

- Methods for mission mapping and dependency analysis within complex systems; going beyond computer and network assurance to mission assurance.

- Design of trustable systems composed of both trusted and untrusted hardware and software; study of virtualization and trusted platforms
- Algorithms and innate mechanisms that enable systems to automatically continue correct operation when presented with unanticipated input or in the face of an undetected bug or vulnerability – this includes adapting fault tolerance for cyber defense.
- Techniques that can disrupt an attack during its early stages (reconnaissance, planning, and testing), such as polymorphism, agility, and randomization, at all layers of networking and computer architectures, to reduce the attackers' understanding of our systems and their ability to launch attacks, while maintaining our own situation awareness: "moving target defenses."
- The ability of information systems to "fight through" attacks, without operator intervention, in a contested environment characterized by "zero day" attacks.
- Examination of assumptions, mechanisms, and implementations of security features that may be adequate for wired networks and devices but provide opportunities for attacks on wireless and mobile systems.
- Theories of complex systems describing interactions of large systems and systems of systems that lead to better understanding of their emergent behaviors during attack and reconstitution; epidemiological models that may be used to predict system responses to Internet worms and coordinated attacks as well as analyses of self-healing and self-restoring systems.

Development of new cryptographic techniques is not of interest under this research opportunity.

Formal Methods for Complex Systems

Dilia Rodriguez
(315) 330-4280
Dilia.Rodriguez@us.af.mil

Formal methods have supported the design and analysis of systems in various domains, yet they are not able to extend this success to many of the systems being developed today. To address the increasing complexity of systems, this research area seeks rigorous and formal approaches to the design, specification, and verification of complex systems. It seeks to support investigation on new powerful formal methods: formal models and abstractions that can perspicuously capture the complexity of modern systems and support their formal analysis, compositional verification techniques, and semantically sound integration of formal methods.

Processing and Exploitation

Advanced Applied Analytics for Full Spectrum Targeting and Predictive Consequence Modeling and Analysis

Mark Alford
(315) 330-3802
Mark.Alford@us.af.mil

Critical Infrastructure of socio-economic, power distribution, transportation systems, etc. face threats every single day. As a result of these deficiencies, information is collected resulting in large scale data repositories with four major attributes that must be taken into consideration; Volume, Velocity, Variety and Veracity. Automated algorithms must seamlessly identify, evaluate and prioritize importance based on operational parameters. A researcher is needed to explore large scale data analysis algorithms. The goal is to support command level decision making by increasing real time situational awareness. This will be done by exploring, for example, data sketching and reduction, clustering, advanced data visualization, and analysis tools. The researcher will verify the parallel computing capabilities of software packages and develop Artificial Intelligence (AI) based algorithms for practical implementation of data sketching and reduction. They will also explore clustering as it is applied to different types of data such as text, images, video and numerical data; research advanced data visualization techniques for increased analyst efficiency; and investigate tools for automated analytics and value visualization for increased situational awareness and more accurate command level decision making.

Research interests in this topic include:

- Independent software verification and application to critical infrastructure analysis
- Multi-domain decision systems analysis including dynamic decision making, semi-autonomous decision making
- Selection for reduction and analysis

Quantum Computing Theory and Simulation

Paul Alsing
(315) 330-4960
Paul.Alsing@us.af.mil

Quantum computing research involves interdisciplinary theoretical and experimental work from diverse fields such as physics, electrical and computer science, engineering and from pure and applied mathematics. Objectives of AFRL's Emerging Computing Technology Branch include the development of quantum algorithms with an emphasis on large scale scientific computing and search/decision applications/optimization, implementations of quantum computational schemes with low error threshold rates, implementations of quantum error correction such as topological protection, and the simulation of quantum circuits/computers and quantum error correction schemes with an emphasis on modeling experiments. Topics of special interest include the cluster state quantum computing paradigm, quantum simulated annealing, the behavior of quantum information and entanglement under arbitrary motion of qubits, measures of quantum entanglement, and the distinction between quantum and classical information and its subsequent exploitation.

Advanced Event Detection and Specification in Streaming Video

Alex Aved
(315) 330-4320
Alexander.Aved@us.af.mil

Focus area 1: graph analysis techniques applied to assessing the resilience of critical infrastructure systems (e.g. electric power grid, communications systems); to include sets of critical nodes and links, measures of centrality, dimensionality reduction, application of game theory, graph matching and alignment with large sparse graphs, and corresponding metrics to characterize assessments and data fitness, and related areas.

Focus area 2: distributed computation and reasoning of near real-time stream data processing (e.g., full motion video) for situational awareness. A query-based approach to analyzing (i.e.: descriptive), understanding (i.e., diagnostic) and predicting (i.e., predictive) situation understanding with real-time feedback (i.e., prescriptive analytics) can be explored. Areas of interest include query robustness (i.e. quality and transactional properties), and applying machine learning (statistical) techniques with dynamic feedback loops measure to measure and adjust model fitness; applied to real-time streaming video. (Reference AFOSR's Dynamic Data Driven Applications Systems (DDDAS) portfolio description or the community at www.1dddas.org.)

Big Data Analytics for Activity Based Information

Chris Banas
(315) 330-2202
Christopher.Banas.1@us.af.mil

AFRL seeks innovative research in the area Big Data Analytics for Activity Based Information (ABI). More specifically, AFRL seeks automated or semi-automated procedures to characterize and locate activities and actions/transactions, identify and locate actors and entities conducting the activities and transactions, determine the existence, topology, leadership, and other characteristics of covert networks, understand the relationships between networks, and determine patterns of life from large amounts of externally observed data. Research interests also include the discovery and understanding of unknown activities and associated trends/patterns/ relationships. In addition, these techniques should move beyond the limitations of traditional approaches to consider temporal dynamics and\or multi-modal networks and are most interesting when researched in the context of a variety information sources and types and the challenges presented by "Big Data."

Explanation of Failure States within Machine Learning Models

Walter Bennette
(315) 330-4957
Walter.Bennette.1@us.af.mil

The need for increased levels of autonomy has significantly risen within the Air Force. Thus, machine learning tools that enable intelligent systems have become essential. However, analysts and operators are often reluctant to adopt these tools due to a lack of understanding – treating machine learning as a black box that introduces significant mission risk. Although one may hope that improving machine learning performance would address this issue, there is in fact a trade-off: increased effectiveness often comes at the cost of increased complexity. Increased complexity then leads to a lack of transparency in understanding machine learning methods. In particular, it becomes unclear when such methods will succeed or fail, and why they will fail. This limits the adoption of intelligent systems.

This topic focuses on the explanation of failure states within machine learning models to non-machine learning experts. Here, failure states are defined to be areas of the feature space where the model systematically makes incorrect inferences, not random errors. It is believed that techniques to explain failure states can help build confidence in machine learning models, and consequently, promote the adoption of specific intelligent systems. We are interested in pursuing techniques for a variety of machine learning problems, but special emphasis is placed on domain and model agnostic approaches. Areas of interest include, but are not limited to, classification, computer vision, planning, and representation learning.

Methods for Adapting Pre-Trained Machine Learning Models

Maria Cornacchia
(315) 330-2296
Maria.Cornacchia@us.af.mil

Numerous machine learning algorithms have recently made remarkable advances in accuracies due to more standardized large datasets. Yet, designing and training an algorithm for large datasets can be time-consuming and there may be other tasks or activities for which less data exists. There is a large body of work showing the performance benefits of fusing models for the same task. Hence, the ability to adapt and fuse pre-trained models has the advantages of fewer data requirements and decreased computing resources.

The purpose of this topic will be to develop novel methods for fusing and building ensembles of pre-trained machine learning models that are task agnostic and can more closely mimic the agility that humans possess in the learning process. This topic is particularly interested in exploring and evaluating architectures and methods that involve the fusion of Convolutional Neural Networks (CNNs) or other deep learning methods. CNNs have been one class of learning algorithm that have greatly improved accuracies over numerous application domains, including computer vision, text analysis, and audio processing. Additionally, another area of interest includes methods that explain the numerical impacts of training examples on the models being learned. In other words, novel methods that conceptually describe what an algorithm is learning. Both being able to explain the impact of specific examples on the learning process and building novel algorithms and architectures for fusion of pre-trained models will support the realization of more adaptable learning methods.

Quantum Information Processing

Michael Fanto
(315) 330-4455
Michael.Fanto@us.af.mil

The topic of Quantum Information Processing is to be focused on Computational Methods and Architectures. It has been well established that a computer based on quantum interference could offer significant increases in processing efficiency and speed over classical versions, and specific algorithms have been developed to demonstrate this in tasks of high potential interest such as data base searches, pattern recognition, and unconstrained optimization.

However the present experimental progress, lagging far behind the theoretical, is at the level of several gates or Q bits. The entangled photon approach to quantum gates including quantum gates, cluster states, and Linear Optical Quantum Computing will be experimentally pursued with particular attention to scalability issues. Experience with generation and detection of entangled photons is essential for this interaction, with parametric amplification a plus.

Theoretical advances will also be pursued with existing and custom quantum simulation software to model computational speedup, error correction and de-coherence effects. Algorithm

investigation will focus on hybrid approaches which simplify the physical realization constraints and specifically address tasks of potential military interest.

Audio Processing

Darren Haddad
(315) 330-2906
Darren.Haddad@us.af.mil

The Audio Group in AFRL/RIGC is involved in all aspect of speech processing and is a unique combination of linguists, mathematicians, DSP engineers, software engineers, and intelligence operators. This combination of individuals allows us to tackle a wide spectrum of topics from basic research such as channel estimation, robust word recognition, language and dialect identification, and confidence measures to the challenging transitional aspects of real-time implementation, GUI design, and concepts of operations. The Audio Group also has significant thrusts in noise estimation and removal, speaker identification including open-set identification, keyword spotting, robust feature extraction, language translation, analysis of stressed speech, coding algorithms along with the consequences of the compressions schemes, watermarking, co-channel mitigation, and recognition of background events in audio recordings. SOA techniques such as I-vectors, deep neural networks, bottleneck features, and extreme learning are used to pursue solutions for real-time and offline problems such as SID, LID, GID, etc,

Motion Imagery (or Video) Processing and Exploitation

Todd Howlett
(315) 330-4592
Todd.Howlett@us.af.mil

Motion Imagery sources include everything from airborne collectors to YouTube. New and innovative technology is required to exploit and extract the relevant information content and manage the whole exploitation process. Visual processing is the focus, but leveraging all aspects of the data is of interest (e.g. audio and metadata) as well as using any additional correlating sources (e.g. reference imagery or coincident sensors). Both semi-automated and fully automated capabilities are of interest. Emphasis will be on overcoming or working around the current limit of computer vision to lead to a useful capability for an AF analyst. Sample topics of interest would be: biologically inspired techniques, scene classification, event detection, object detection and recognition, optimization techniques, Bayesian methods, geo-registration, indexing, etc.

Risk-Aware, Distributed Information Gathering

Jeffery Hudack
(315) 330-2963
Jeffery.Hudack@us.af.mil

Future missions will need to achieve information gathering and processing in a distributed environment while being resilient against dynamic and adverse conditions. Research areas of interest include distributed control, risk-aware planning, and federated information management. Distributed control considers methods of coordination between multiple systems that are not governed by a central authority. Risk-aware planning is a form of robust optimization that considers the inherent risks in the environment, both natural and adversarial. Federated information management includes the transport, processing and fusion of data through the interaction of multiple dispersed devices. These research areas are of growing interest applied to command and control, man-machine interactions, and the maturation of unmanned air vehicles. Evaluation of distributed methods will be performed using empirical simulation, quantitative dynamic models, and/or verification via formal proof.

Web Browser Extension Development and Data Extraction

Michael Manno
(315) 330-7517
Michael.Manno@us.af.mil

The primary objective of the this effort is to extract information from documents in real time, without the need to install an additional a software package, specialized development, or trained agents to each source.

Seeking data from multiple documents is a manual, time consuming, undocumented process which needs to be repeated every time an update, or change, to that data is requested. Automating this process is a challenge because the documents routinely change. Sometimes, the mere act of refreshing a web page changes the document as the ads cycle. Such changes are damaging to most of today's web scraping techniques. The lack of data from failed updates during the extraction process creates many problems when attempting to update data that is located from open source web sites, and documents. Each time a document changes, the method associated with that document responsible for the data extraction also needs to change. This diverts time away from an analyst, as the analyst begins spending more time managing data, opposed to performing the intended analysis. Web scraping, or extracting data from a document, typically requires training or expert analysis of each source before data can be parsed from it. This means documents must first be identified before a script or agent can be written to extract data from it. This process does not allow a user to discover a document and immediately being parsing data from it. Services that provide access to data such as RSS feeds, Web Services, and APIs, are useful, but are not necessarily what is needed by the requestor. For example, the Top Story from a news publisher may be available as an RSS feed, whereas the birth rate of the country may not be.

This assignment will focus heavily on enhancing a web browser extension designed to leverage the Air Force Research Laboratory, AFRL in-housed developed functionality, and web browser functionality, in an extension called Atlas. The extension will be used for routine extraction of data elements from open source web pages/documents, and be developed for the Firefox web browser. In addition to Web Browser extension development, this assignment will also be involved with adding additional functionality such as visualization enhancements, search and transposition, crawl, and a process for identifying similar data. Consideration will also include expanding to additional web browsers such as Internet Explorer.

Dynamical Reservoir Computing

Nathan McDonald
(315) 330-3804
Nathan.McDonald.6@us.af.mil

Recent advancements in nanoelectronics, photonics, neuromorphic systems, and cognitive neuroscience are enabling the development of radically different computational architectures based on reservoir computing concepts. Such systems are theoretically capable of solving the toughest temporal/spatial classification and regression problems with Air Force applications focused on increased system autonomy and perception. This research explores a new class of computationally intelligent processers governed by the nonlinear dynamics within oscillating optical or electronic reservoirs. The nonlinear dynamics and delayed feedback (short term memory) of reservoirs enable networks to mimic transient neuronal responses and to project time dependent input into high dimensionalities for categorization by an outside classifier. Such hardware based reservoirs can operate near the edge of chaos providing extreme sensitivity to input variations for increased degrees of separability between input signatures. In this context, the reservoirs function as time delayed recursive networks that utilize feedback as short term dynamic memory for the processing of time-series input signals. These systems offer potentially disruptive capabilities in real time signature analysis, time-series predictions, and environmental perception for autonomous operations. Interests associated with this topic include; exploration of the required properties and associated mechanisms to build efficient reservoirs, system modeling, spike-timing-dependent plasticity (STDP), memristive systems, and cortical architectures, with emphasis on bio-inspired computational schemes based on the physics of nonlinear systems.

Optical Interconnects

Joseph Osman
(315) 330-7671
Joseph.Osman@us.af.mil

Our main area of interest is the design, modeling, and building of interconnect devices for advance high performance computing architectures with an emphasis on interconnects for quantum computing. Current research focuses on interconnects for quantum computing including switching of entangled photons for time-bin entanglement.

Quantum computing is currently searching for a way to make meaningful progress without requiring a single computer with a very large number of qubits. The idea of quantum cluster computing, which consists of interconnected modules each consisting of a more manageable smaller number of qubits is attractive for this reason. The qubits and quantum memory may be fashioned using dissimilar technologies and interconnecting such clusters will require pioneering work in the area of quantum interconnects. The communication abilities of optics as well as the ability of optics to determine the current state of many material systems makes optics a prime candidate for these quantum interconnects.

Extracting Knowledge from Text

Aleksey Panasyuk
(315) 330-3976
Aleksey.Panasyuk@us.af.mil

AFRL is interested in exploring recent machine learning advances via neural networks such as Recurrent Neural Networks (RNN) combined with Conditional Random Fields (CRF), Long Short-Term Memory (LSTM) networks, Convolutional Neural Network (CNN), and potentially others for improving extraction capabilities from text. The challenge would be to setup the network in-house, replicate performance on a known dataset, and then test on internal AFRL data. Examples of information that can be extracted from text include: (1) people and groups, (2) events (who, what), (3) geo-spatio-temporal information (where, when), (4) causal explanations (why, how), (5) facilities and equipment, (6) modality and beliefs, (7) anomaly, novelty, emerging trends, (8) interrelationships, entailments, coreference of entities and events, (9) disfluencies/disjointedness, (10) dynamic, perishable, changing situations. It is preferable that the learning environment is setup via known packages such as TensorFlow or Torch.

Mathematical Theory for Advances in Machine Learning and Pattern Recognition

Ashley Prater
(315) 330-2804
Ashley.Prater.3@us.af.mil

To alleviate the effects of the so-called 'curse of dimensionality', researchers have developed sparse, hierarchical and distributed computing techniques to allow timely and meaningful extraction of intelligence from large amounts of data. As the amount of data available to analysts continues to grow, a strong mathematical foundation for new techniques is required. This research topic is focused on the development of theoretical mathematics with applications to machine learning and pattern recognition with a special emphasis on techniques that admit sparse, hierarchical or parallelizable numerical methods. Research may be performed in, but not limited to: sparse PCA, generalized Fourier series, low-rank matrix approximation and compressed sensing. Proposals with a strong mathematical foundation will receive special consideration.

Advanced Computing Processors Information Management

George Ramseyer
(315)-330-3492
George.Ramseyer@us.af.mil

As the number of computing processors is increased for most applications, a situation is reached where processor information management becomes the bottleneck in scaling, and adding additional processors beyond these number results in a deleterious increase in processing time. Some examples that limit scalability include bus and switch contentions, memory contentions, and cache misses, all of which increase disproportionally as the number of processors increase. The objective of this topic is to investigate existing and/or to develop novel methods of processor information management for multiprocessor and many-processor computing architectures that will allow for increased scaling.

Data Driven Model Discovery for Dynamical Systems

Joseph Raquepas
(315) 330-4263
Joseph.Raquepas@us.af.mil

The discovery and extraction of dynamical systems models from data is fundamental to all science and engineering disciplines, and the recent explosion in both quantity and quality of available data demands new mathematical methods. While standard statistical and machine leaning approaches are capable of addressing static model discovery, they do not capture interdependent dynamic interactions which evolve over time or the underlying principles which govern the evolution. The

goal of this effort is to research methods to discover complex time evolving systems from data. Key aspects include discovering the governing systems of equations underlying a dynamical system from large data sets and discovering dynamic causal relationships within data. In addition to model discovery, the need to understand relevant model dimensionality and dimension reduction methods are crucial. Approaches of interest include but are not limited to: model discovery based on Taken's theorem, learning library approaches, multiresolution dynamic mode decomposition, and Koopman manifold reductions.

Uncertainty Propagation for Space Situational Awareness

Joseph Raquepas
(315) 330-4263
Joseph.Raquepas@us.af.mil

One of the significant technical challenges in space situational awareness is the accurate and consistent propagation of uncertainty for a large number of space objects governed by highly nonlinear dynamics with stochastic excitation and uncertain initial conditions. Traditional uncertainty propagation methods which rely on linearizing the dynamics about a nominal trajectory often break down under a high degree of uncertainty or on long time scales. In addition the data uncertainty is usually poorly characterized or the data may be sparse or incomplete. Many recent developments which attempt to address these issues such as the unscented Kalman filters, Gaussian sum filters, and polynomial chaos filters tend to be ad hoc approaches with limited foundational rigor. The objective of this topic is to research accurate, computationally efficient, and rigorously validated methods for uncertainty propagation for the dynamical systems which address the nonlinear nature of the underlying dynamics, and the high degree of uncertainty and lack of completeness in the data. Of interest are approaches which leverage methods of modern dynamical systems theory, theory of stochastic differential equations, unique methods for numerically approximating solutions to the Fokker-Planck equation.

Many-Node Computing for Cognitive Operations

Thomas Renz
(315) 330-3423
Thomas.Renz@us.af.mil

The sea of change in computing hardware architectures, away from faster cycle rates and towards processor parallelism, has expanded opportunities for development of large scale physical architectures that are optimized for specific operations. Porting of current cognitive computing paradigms onto systems composed of parallel mainstream processors will continue in the commercial world. What higher cognitive functionality could we achieve if we take better advantage of physical capabilities enabled by new multi-processor geometries?

Perception, object recognition and assignment to semantic categories are examples of lower level cognitive functions. Assignment of valence, creation of goals and planning are mid level functions. Self awareness and reflection are higher level processes that are so far beyond current cognitive

systems that relatively little has been done to model the processes. Often, models assume higher cognitive processes will emerge, once the computing system reaches some level of speed / complexity. The problem is that the computational power required exceeded the reachable limit of single processor architectures and probably exceeds the limits of conventional parallel architectures. This topic seeks to enable mid and higher level cognitive function by creation of new physical architectures that address the computation demand in novel ways.

We are interested in developing models for the computational scale of the mid and higher functions and processor / memory node architectures that facilitate cognitive operations by configuring the physical architecture to closely resemble the functional cognitive architecture, e.g., where each node in a network represents and functions as a processor for a single semantic primitive. What new hierarchical architectures could we design for million node systems, where the individual nodes may be small ASPs, with very fast communication between nodes? A project of interest would combine both sides, new algorithms for higher level cognitive functions and new architectures to enable the computation in a realistic time frame. AFRL/RIT has projects on line to enable million node systems.

Secure Processing Systems

John Rooks
(315) 330-2618
John.Rooks@us.af.mil

The objective of the Secure Processing Systems topic is to develop hardware that supports maintaining control of our computing systems. Currently most commercial computing systems are built with the requirement to quickly and easily pick up new functionality. This also leaves the systems very vulnerable to picking up unwanted functionality. By adding specific features to microprocessors and limiting the software initially installed on the system we can obtain the needed functionality yet not be vulnerable to attacks which push new code to our system. Many of these techniques are known however there is little commercial demand for products that are difficult and time consuming to reprogram no matter how much security they provided. As a result the focus of this topic is selecting techniques and demonstrating them through the fabrication of a secure processor. Areas of interest include: 1) design, layout, timing and noise analysis of digital integrated circuits, 2) Implementing a trusted processor design and verifying that design, 3) Selection of security features for a microprocessor design, 4) verifying manufactured parts, and 5) demonstrations of the resulting hardware.

Data-Efficient Machine Learning

Lee Seversky
(315) 330-2846
Lee.Seversky@us.af.mil

Eric Heim
(315) 330-7084
Eric.Heim.1@us.af.mil

Many recent efforts in machine learning have focused on learning from massive amounts of data resulting in large advancements in machine learning capabilities and applications. However, many domains lack access to the large, high-quality, supervised data that is required and therefore are unable to fully take advantage of these data-intense learning techniques. This necessitates new data-efficient learning techniques that can learn in complex domains without the need for large quantities of supervised data. This topic focuses on the investigation and development of data-efficient machine learning methods that are able to leverage knowledge from external/existing data sources, exploit the structure of unsupervised data, and combine the tasks of efficiently obtaining labels and training a supervised model. Areas of interest include, but are not limited to: Active learning, Semi-supervised leaning, Learning from "weak" labels/supervision, One/Zero-shot learning, Transfer learning/domain adaptation, Generative (Adversarial) Models, as well as methods that exploit structural or domain knowledge.

Furthermore, while fundamental machine learning work is of interest, so are principled data-efficient applications in, but not limited to: Computer vision (image/video categorization, object detection, visual question answering, etc.), Social and computational networks and time-series analysis, and Recommender systems.

Feature-Based Projection of Threats

Carolyn Sheaff
(315) 330-7147
Carolyn.Sheaff@us.af.mil

Methods have been developed to detect anomalous behaviors of adversaries as represented within sensor data, but autonomous projections of actual threats to US assets require further investigation and development. The proposed research will investigate and develop both the foundation and the algorithms that can predict the type of threat a red asset poses to a blue asset. The inputs to the system may include: 1) an indication/warning mechanism that indicates anomalous behavior exists, and 2) a classification of the type of red/blue asset. Approaches to consider include, but not limited to, projections based on offensive/defensive guidance templates and techniques associated with machine learning. The approach can be applied to any threat domain. The example that follows illustrates application to U.S. satellite protection. The offensive template determines the type of threat. The classification algorithm provides notification of the type of asset it is. The classification approach is employed to (for example) determine whether the asset is intact or a fragment, its control states, the type of control state, and whether it is a rocket body, payload, or

debris. An example of an offensive assessment is a mass-inertia configuration change in an active red asset that is specific for robotic arm-type movements. Mechanisms such as templates are used to project whether or not this asset is a threat by comparing configuration changes with known threatening scenarios through probabilistic analyses, such as Bayesian inferences. Robustness tests may be employed as well. For example, a threat can be simulated that is not specific to one template. The question to be answered is: can a combination of the templates handle this case? The defensive portion must provide countermeasures, i.e. as in the case of a blue satellite, thruster burns to move away from possible threats.

Communications Processing Techniques

Doug Smith
(315) 330-3474
Douglas.Smith.44@us.af.mil

We are focusing our research on exploring new and novel techniques to process existing and future wireless communications. We are developing advanced technologies to intercept, collect, locate and process communication signals in all parts of the spectrum. Our technical challenges include: interference cancellation in dense co-channel environments, multi-user detection (MUD) algorithms, hardware architecture and software methodologies, techniques to geo-locate and track emitters and methodologies to improve the efficiency of signal processing software. Research into developing unique and advanced methods to process communication signals in a high density, rapidly changing environment is of great importance. The research is expected to be a combination of analytical and experimental analyses. Experimental aspects will be performed via simulations using an appropriate signal processing software tool, such as MATLAB.

Optimization for Pattern Analysis

Bruce Suter
(315) 330-7563
Bruce.Suter@us.af.mil

In aerospace systems, there is a growing gap between the amount of data generated and the amount of data that can be stored, communicated, and processed. Moreover, this gap keeps widening. One promising approach to solving this problem is to utilize optimization to reliably extract patterns for large scale data. This topic addresses the theory and application of optimization for pattern analysis. This includes:

- Development of an optimization-based theoretical framework for pattern analysis. Some promising directions are based in part on the study of multilevel and nonconvex optimization.

- Optimization applications may permit novel computational paradigms, such as computation of numerical rank, which is critically important for machine learning and signal processing.

Neuromorphic Computing

Clare Thiem
(315) 330-4893
Clare.Thiem@us.af.mil

Neuromorphic computing shows great promise in the development of intelligent systems able to imitate natural neuro-biological processes such as reasoning and perception. This is achieved by artificially recreating the highly parallelized computing architecture of the mammalian brain. In particular, neuromorphic computers are suitable for applications in control systems, pattern recognition and optimization, i.e., automated data processing, intelligence analysis, etc. In order to achieve high levels of intelligence within systems, neuromorphic computing exploits the characteristic behavior of novel complex materials and structures with advanced processing techniques to achieve very large scale integration with highly parallel neural architectures. This research effort will focus on mathematical models, computing architectures and computational applications to develop neuromorphic computing processors. Also of interest, is the development of neuromorphic computing architecture software emulation and hybrid VLSI CMOS architectures utilizing nano- scale technologies. Special emphasis will be placed on promising technologies and solutions to satisfy future Air Force needs employing intelligent systems to achieve the desired level of autonomy.

Nanocomputing

Joseph Van Nostrand
(315) 330-4920
Joseph.VanNostrand@us.af.mil

Advances in nanoscience and technology show great promise in the bottom-up development of smaller, faster, and reduced power computing systems. Nanotechnology research in this group is focused on the development of crossbar computing architectures which utilize existing nanotechnologies including nanowires, coated nanoshells, memristors, and carbon nanotubes and are scalable to 100x100 arrays. We have a particular interest in the modeling and simulation of architectures that exploit the unique properties of these new and novel nanotechnologies. This includes development of nonlinear sub-circuit models that accurately represent sub-circuit performance with subsequent CMOS integration. Also of interest are the use of nanoelectronics and thermal management techniques using nanotechnologies in 3D computer architectures.

Event Detection and Predictive Assessment in Near-real Time Complex Systems

Alfredo Vegairizarry
(315) 330-2382
Alfredo.Vegairizarry.1@us.af.mil

Making best use of multi-point observations and sensor information for event detection and predictive assessment in complex, near real time systems is a challenge which presents itself in many military domains. The first step in tackling these challenges is to analyze and understand the data. Depending on the algorithm used to detect an anomalous event, the nature and extent of variable correlations must be understood. This research will consider methods to quantify the strength of the correlations of input variables to output variables and develop techniques to account for lag times in the data itself. This is no easy task since sensor readings and operator logs are sometimes inconsistent and/or unreliable, some catastrophic failures can be almost impossible to predict, and time lags and leads in real world systems may vary from one day to the next. After detecting where the strongest correlations exist, one must choose a model which can best assess the current conditions and then predict the possible outcomes that could occur for a number of possible scenarios. Scientific issues of interest include, but are not limited to (1) advanced statistical methods to determine dependencies between senor inputs and the combined effect of multiple-sensors (2) adaptive correlation analysis techniques which will evolve to discover new dependencies in time as conditions change (3) adaptive pattern matching methods to take correlated sensor inputs and characterize normalcy and anomalous conditions.

Towards Precise Low Level Program Analysis

Lok Yan
(315) 330-2756
Lok.Yan@us.af.mil

Program analysis has traditionally been separated into two categories – dynamic and static. In dynamic analysis the sample under test is executed and its runtime behavior is analyzed. In static analysis, the sample is analyzed at rest. The main benefit of static analysis is code coverage, (e.g., the full control flow graph of a sample can be built) however, its main disadvantage is the lack of runtime or concrete data values. Conversely, the advantage of dynamic analysis is the availability of concrete information and the disadvantage is the lack of coverage. Thus, program analysis in practice is likely to use both static and dynamic techniques.

There are also different dimensions to program analysis. Analysis-granularity is one of them. For obvious reasons, analyzing a program at a high level representation (e.g., source code) can benefit from the available contextual information which is lost when a program is analyzed at a lower level (e.g., assembly). This loss of high level information, in turn, leads to a loss of precision (i.e., increase in false positives). Unfortunately, low level analysis is the only viable approach for many applications. For instance, malware samples normally arrive as binaries and not as source code.

The main goal of this topic is to investigate techniques that can be used to increase the precision of low level analysis. To put it differently, how can we make low level analysis as precise possible with the upper bound being high level analysis? The proposed work should initially focus on individual sub problems in program analysis – information flow, control dependency, etc.

Information Institute
26 Electronic Pkwy
Rome, NY 13441
P# 315-330 3251
F# 315-330-4547